Title: **Laser Doppler vibrometer validation of an optical flow motion tracking algorithm**

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Abstract

Background: The use of single point laser Doppler vibrometer is well established for evaluating displacement or validation in many applications such as scientific research, defence, manufacturing, and biomedicine with other techniques. In this research, breast shaped fabricated phantoms are used in laser Doppler vibrometery to validate the optical flow motion measuring algorithm used in a mechanical vibration based breast cancer screening system.

Methods: Three different silicone phantoms were used: healthy; 10 mm inclusion and 20 mm inclusion. The overall goal was to use single point laser Doppler vibrometer data to validate digital image-based elasto-tomography (DIET) motion data from optical flow tracking at frequencies of 16 Hz, 24 Hz, 32 Hz, and 40 Hz.

Summary of findings: Results show excellent validation with errors less than 6 % for healthy phantom, and errors less than 8 % for 10 mm inclusion and 20 mm inclusion.

Conclusions: The overall results from the optical flow motion algorithm used with DIET and a laser Doppler vibrometer at every frequency show the optical flow algorithm captures surface motion of breast shaped silicone phantoms with good accuracy. The optical flow algorithm is thus suitable and robust enough for use in clinical breast screening. Finally, the errors presented quantify explicitly the error of this algorithm verses this laser-based gold standard.

Keywords:

Digital image-based elasto-tomography; Breast cancer; Optical flow; Laser Doppler vibrometer

1. Introduction

Early detection of breast cancer improves treatment effectiveness and enhances the odds of survival. The most typical breast cancer screening methods [1], include MRI [2] and mammography [3]. However, due to drawbacks and limitations around cost, discomfort, and invasiveness, there is need of better screening techniques.

Digital image elasto tomography (DIET) is a non-invasive, pain-free breast cancer screening technique. It analyses local tissue stiffness based on elastographic reconstruction [4-8]. In particular, DIET captures steady state surface motion in response to 16 – 50 Hz low amplitude sinusoidal mechanical actuation applied to the breast [9], and identifies regions of high underlying stiffness, leveraging the high contrast between healthy and cancerous tissues [7].

DIET currently uses an optical flow (OF) algorithm for this purpose, tracking up to 15000 points on a breast surface [10]. However, the errors of this method have never been explicitly quantified.

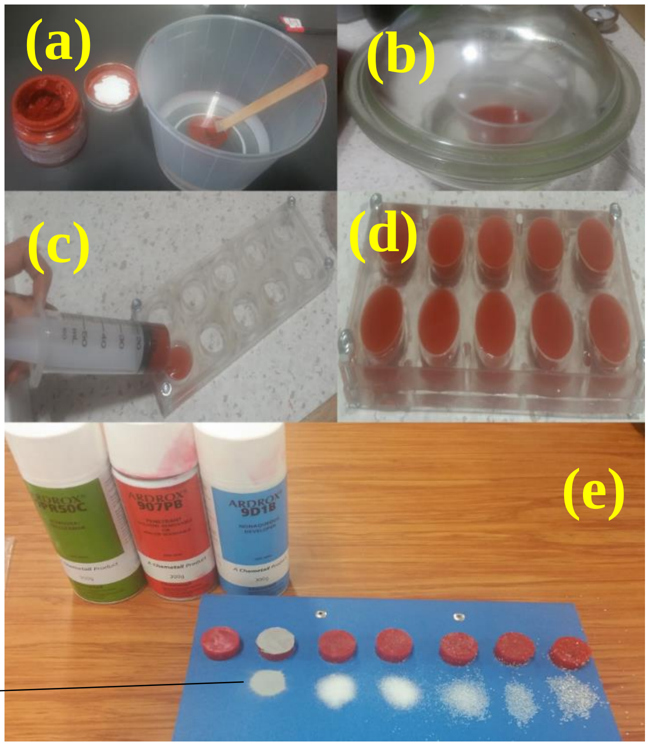
Laser Doppler vibrometers (LDVs) are devices used to measure the instantaneous velocity or displacement of vibrating surfaces. A displacement measurement provides useful information for medical application. The laser vibrometer is a remote measurement device as it measures vibration from a distance without contact. Laser measurement is considered the most promising three-dimensional measurement method, due to its high resolution and non-destructive non-contact modality. Biomedical applications of this measure such as 3D scanning, include anatomical reconstruction [11], orthodontic treatment planning [12], cranial deformation research [13], cartilage morphology studies [14], anthropometric data collection [15], and various forms of surgery.

However, there are also several limitations. Laser line of sight requirements makes measurement demanding, especially on complicated 3D geometries, such as a breast. Measurement quality also depends upon surface quality, particularly a laser beam strikes an optically rough surface, such as skin, where the laser wavelength (633 nm for the red HeNe laser) is on the scale of surface roughness. Reflective tape is thus a commonly used surface treatment in laser vibrometer measurements to maximise the return light intensity [16]. However, overall, it is not a suitable replacement for OF, but would be useful to validate its measured motions. In this paper, a single point laser Doppler vibrometer is used to validate horizontal out of plane measurements calculated using OF for a series of breast shaped phantoms.

2. Materials and Method

2.1 Sample Preparation

Retro-reflective tape is a commonly used surface treatment in laser vibrometer measurements to maximize the return light intensity. Because the silicone surface is oily and tape absorbs oil, different sizes of glass beads and ARDROX were used to test the laser intensity and received signal. Glass beads with mesh size of 100 μm with reflective index ND>1.97 maximise the return light intensity. These materials are shown in Figure 1.



Retro-reflective glass beads with ND>1.97

Figure 1. (a) Mixing pigment with silicone, (b) Removing bubbles from silicone, (c) Pouring exact amount of silicone liquid, (d) Samples fabricated under 50 °C, (e) Reflective glass beads size varies from 500 to 100 μm and ARDROX

Three silicone based homogenous breast shaped phantoms are created. One is homogenous and 'healthy'; the other two have 20 mm and 10 mm inclusions to simulate tumors. Phantom dimensions and fabrication procedures were followed from published reports [17]. There are these three test validation cases.

2.2 Experimental set-up

A laser Doppler vibrometer system made by Polytech (North America, USA) is used. The laser Doppler vibrometer system consists of the OFV-5000 controller and the OFV-512 sensor head. The vibrometer controller delivers signals and power to the sensor head, and processes the vibration signals. These signals are electronically converted by decoders within the vibrometer controller to obtain the displacement.

The light source is a helium neon laser, typically a low-power Class 2 visible laser. The Class 2 laser used in this experiment is considered safe, as the blink response of the human eye is typically considered sufficient to avoid eye damage. However, eyes were still protected with safety glasses.

Steady state mechanical, sinusoidal input oscillations of 16Hz, 24Hz, 32Hz, and 40Hz of low amplitude, 1 mm peak to peak, is applied to the phantom tip, while hanging pendulous [7, 17, 18]. Horizontal out of plane displacements of the phantom surface were measured using laser Doppler vibrometer. The experiments were carried out on top of a vibration isolation table to avoid unnecessary surrounding vibration. The summary of measured points on the phantom surface is shown in Figure 2 and 3. Each phantom was equally divided into 4 sections and 9 surface points were recorded on each section. Therefore, 36 surface points were recorded for each phantom. To ensure reliability, each phantom was tested two times and the average of the resulting peak magnitude displacement was calculated for each phantom and point. As the surface points were marked on each phantom, the laser beam was directed on the same position. Comparisons of surface points serve to validate the accuracy of the DIET surface point OF measurement algorithm.

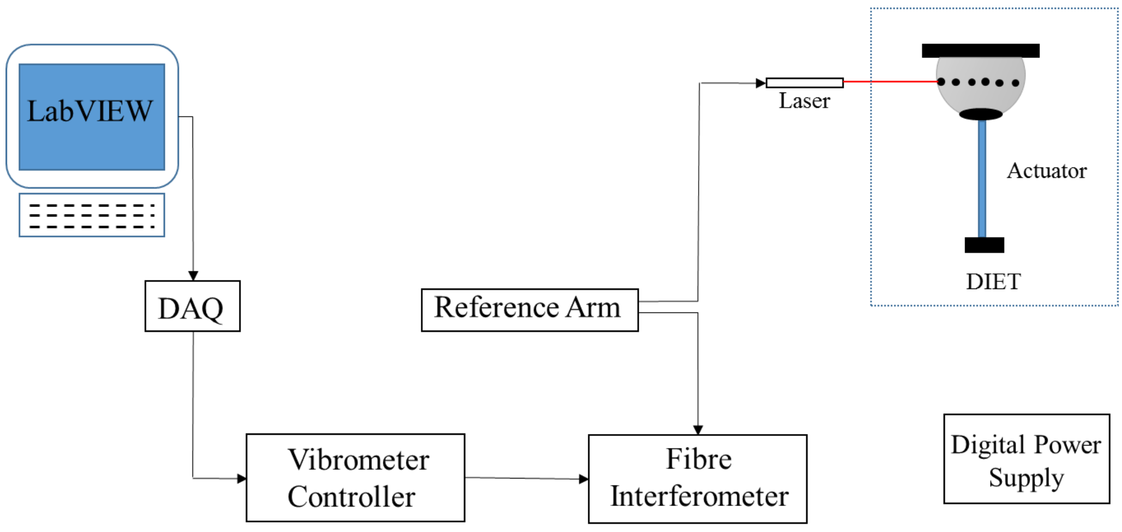


Figure 2. Experimental set-up

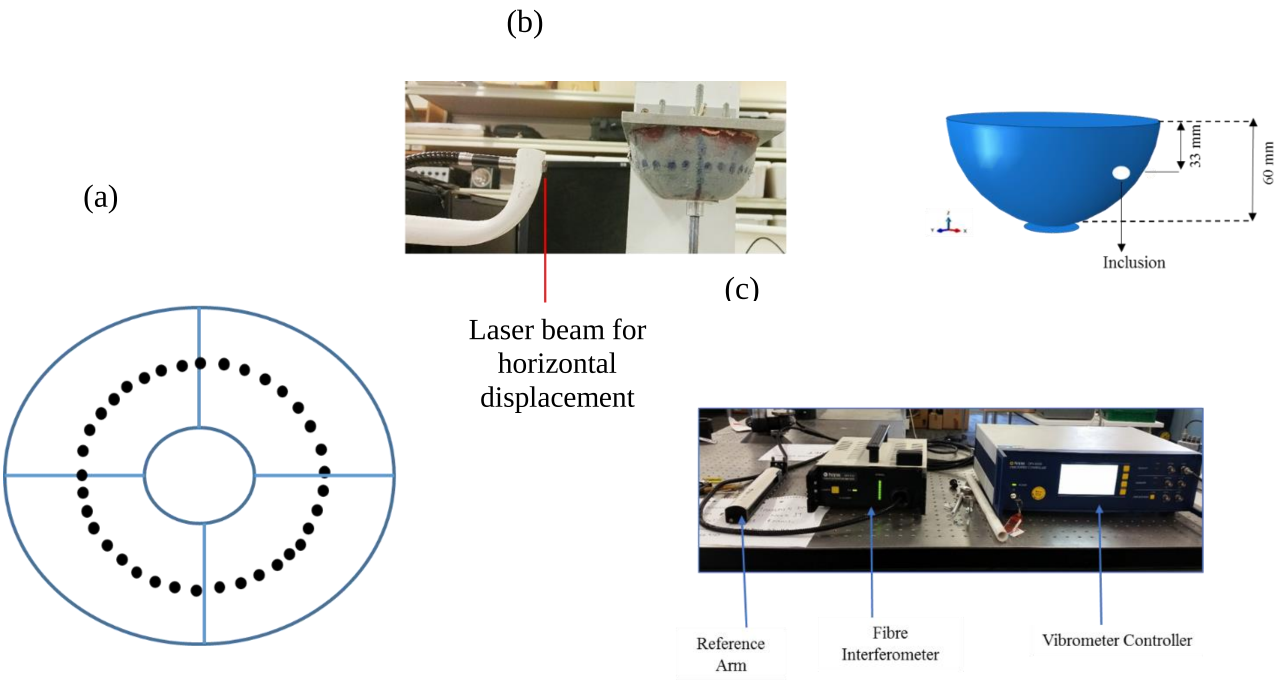


Figure 3. Experimental testing procedure (a) Top view of phantom - summary of marked surface points on the breast shaped healthy, with a 20 mm and a 10 mm inclusions phantom for displacement measurement, (b) Phantom in the DIET, also shown is the geometry dimensions and position of 20 mm and 10 mm inclusion inserted during fabrication (c) laser Doppler vibrometer equipment.

2.3 DIET experimental data

The DIET system images a range of breast shapes and sizes, so the position of the breast and actuator in each image varies between trials. Spherical coordinates (r, θ, φ) are used to estimate a parametric 3D model of the breast surface from frame images, for each of the k = 10 frames imaged over one cycle. A grid of reconstructed 3D surface points is then projected onto the breast image. To estimate surface motion of these points, an optical flow algorithm is applied to pairs of frames [19]. Figure 4 shows points on a breast phantom moving in a single loop direction in response to sinusoidal input after 10 frames in a response cycle. One motion set includes ~15000 points per phantom or breast [19]. Figure 4 shows points on the breast motion after 10 frames. Each frame represents different colour.

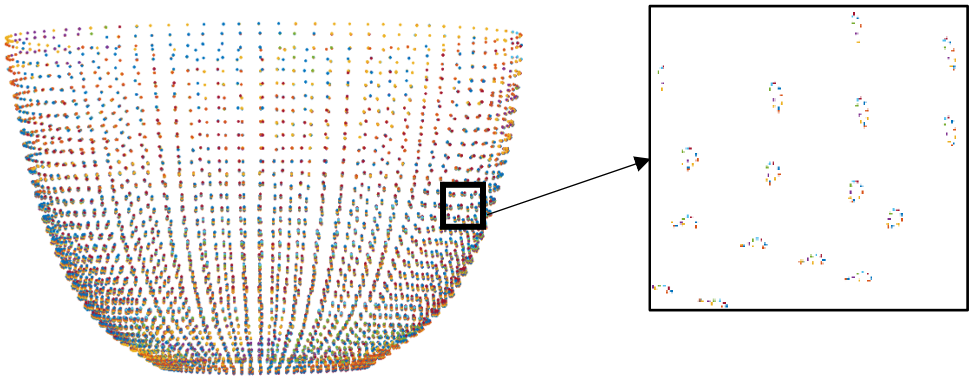


Figure 4. Points on the breast motion after 10 frames. Each frame represents different colour.

A total of three phantoms used in this study, including the no inclusion healthy case. Data from 16 Hz, 24 Hz, 32 Hz and 40 Hz sinusoidal input frequencies with 1 mm amplitude are considered. In each case, a two Newton (2N) preload is also applied, which ensures full contact between the phantom and the actuator and does not squash the phantom.

2.4 Model validation

In this section, positive peak magnitudes of horizontal displacement from the sinusoidal response are compared to those assessed by laser doppler. Horizontal displacements of multiple surface points on the breast shaped phantoms are measured from single point laser Doppler vibrometer. These peak horizontal displacement values are compared to validate the DIET OF derived experimental data. Figure 3 shows the position of surface points on the phantom surface for the three phantom cases tested.

3 Result and discussion

3.1 Validation of DIET OF algorithm

Figure 5 shows LDV measured displacement at 16 Hz input frequency for a single section, which includes N=9 surface points on the healthy, no inclusion phantom. Figures 6 and 7 show the surface positive peak horizontal displacement at frequencies of 16 Hz, 24 Hz, 32 Hz, and 40 Hz on the breast shaped phantom with and without 20 mm and 10 mm inclusions for the laser Doppler vibrometer and DIET experimental data, respectively. There were a total of 36 points measured on each breast phantom.

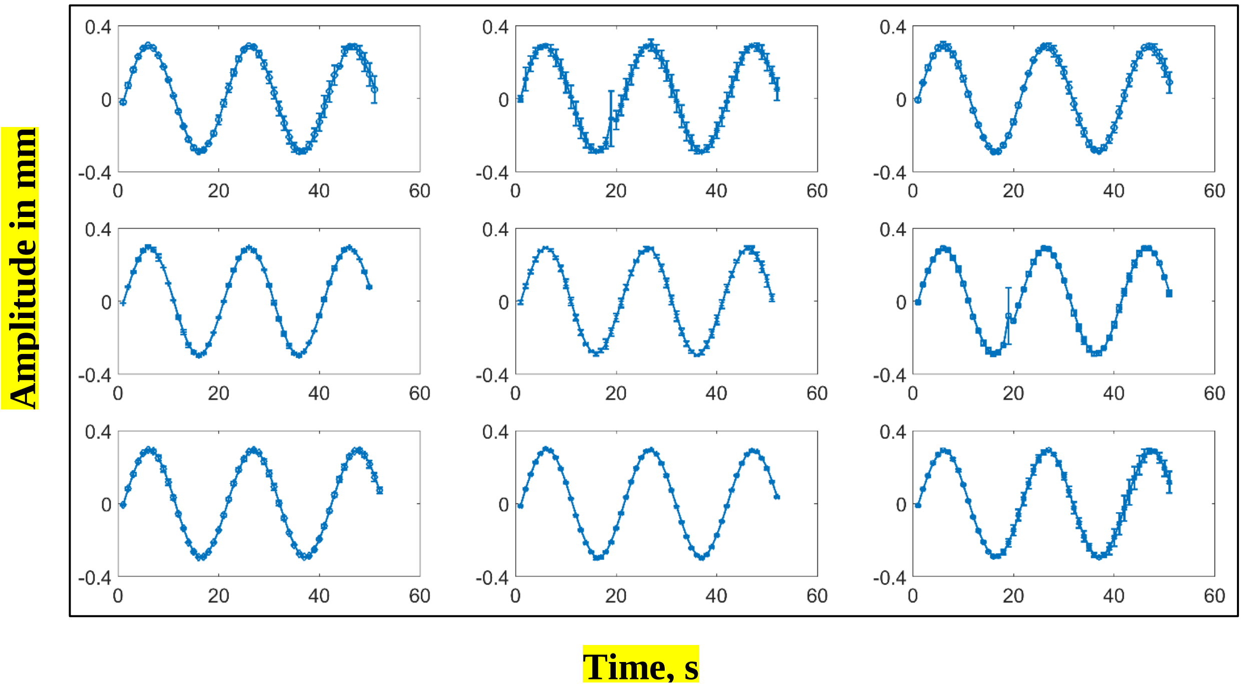
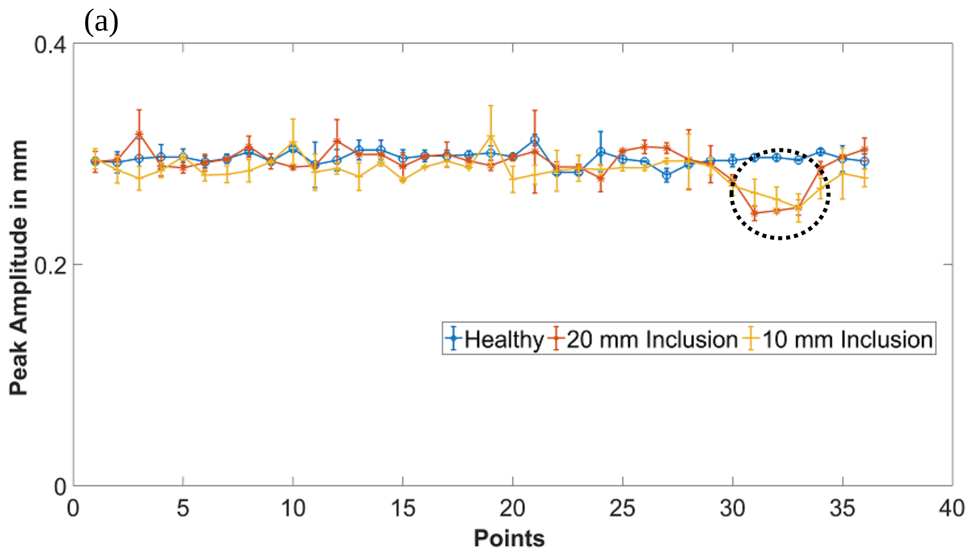


Figure 5. Laser Doppler vibrometer data for 9 points in one section with excitation amplitude of 1mm peak to peak on a healthy phantom surface at 16 Hz sinusoidal excitation.

The fabricated breast phantoms are homogenous and the peak positive horizontal displacement measured from the homogenous healthy phantom are assumed to be the same on all sides. In Figure 6, it can be noticed that the positive peak of horizontal displacement of this healthy phantom for each frequency is almost equal in all sides, as expected. Any fluctuation in points may be due to the misalignment between the phantom surface and the laser beam, as the direction of the laser beam is manually changed to investigate each point on the phantom surface, a main limitation of laser Doppler vibrometer, as any variability in case introduces a systemic bias. It may also be due to small in-homogeneities in the experimental phantom.

It has been well recognised that inclusions are 4-10 times stiffer than the surrounding breast tissues [20]. The tissue displacements are inversely proportional to the stiffness of the tissue. Thus, a stiffer region of tissue exhibits smaller displacements than a more compliant region [6, 7]. The dashed circle shows the peak value of horizontal displacement near the inclusions are smaller than the rest of the sides, as expected. However, the peak displacement magnitude of non-stiffer inclusion regions for both 20 mm and 10 mm inclusion phantoms match well with the magnitude of peak displacement of healthy phantom, which is also as expected.



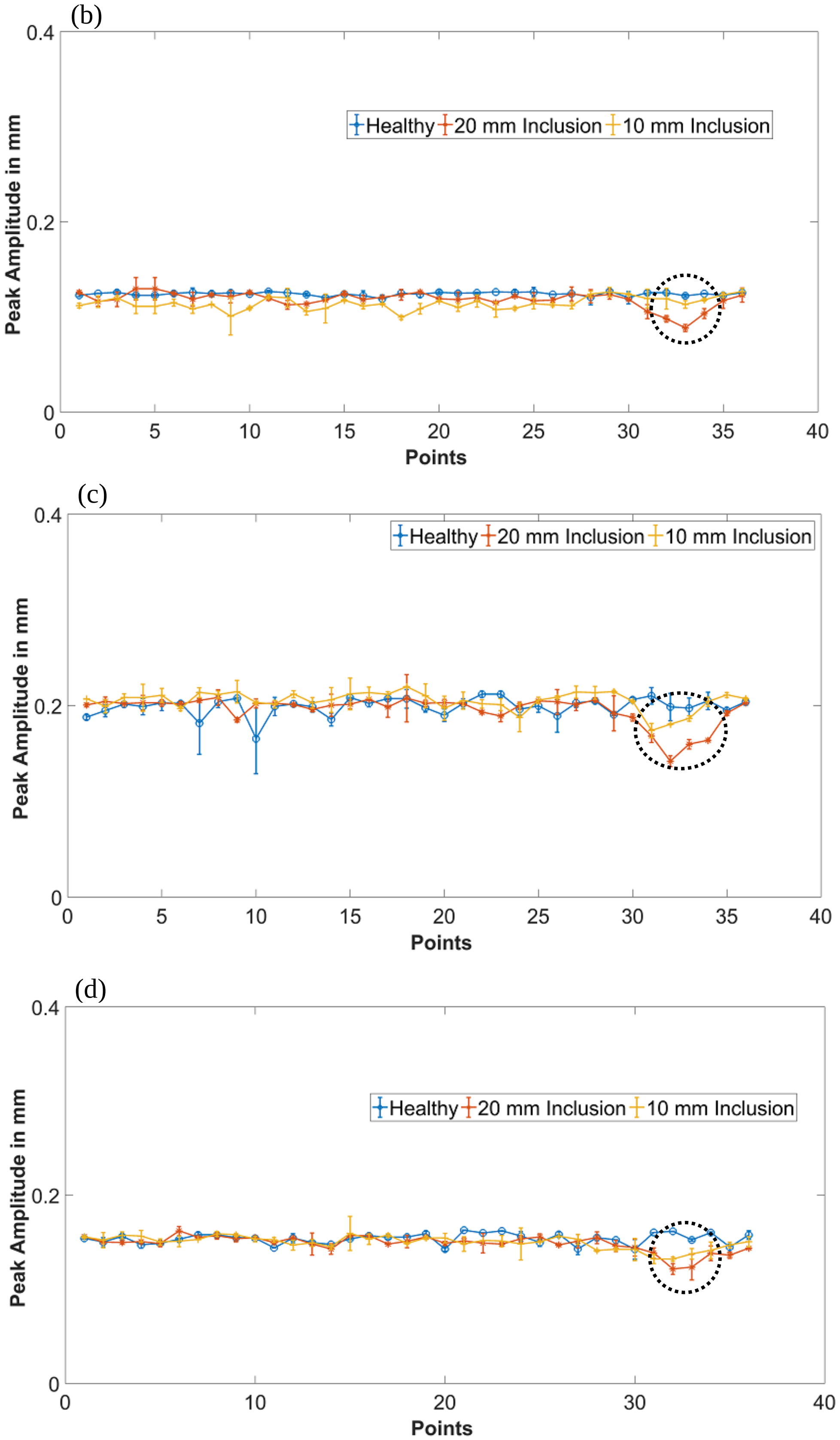
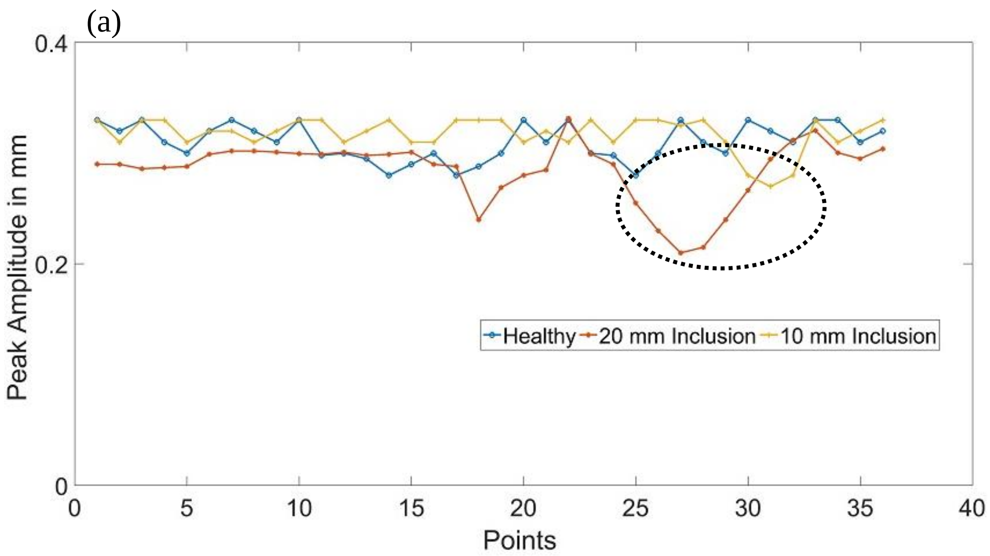


Figure 6. Laser Doppler vibrometer data - excitation amplitudes of 1mm peak to peak on phantom surface (a) 16 Hz excitation; (b) 24 Hz excitation; (c) 32 Hz excitation; (d) 40 Hz excitation

Similarly, Figure 7 shows the peak horizontal displacement values of DIET OF calculated experimental motion data for all three phantoms. It is clear the laser Doppler vibrometer data are less variable than DIET experimental data, as expected. This difference occurs because the laser sensitivity/resolution is high compared to DIET OF reconstruction procedure. In addition, DIET OF experimental motion data are for a 3D model, whereas the laser Doppler vibrometer data are measured in 2D. Finally, the position of the DIET OF data points is not exactly the same as the laser points.

The peak horizontal displacement values for the healthy phantom are almost equal in all frequencies, which shows the phantom is homogenous and is an expected result. For phantoms with inclusions, the displacement near the inclusion is smaller than the surrounding tissues, again as expected. However, the difference for the 20 mm inclusion is bigger than the 10 mm inclusion. Thus, the peak magnitude displacement near the 20 mm inclusion is much smaller than for the 10 mm inclusion phantom and region, which is again as expected, but the difference was larger than seen with the laser Doppler vibrometer



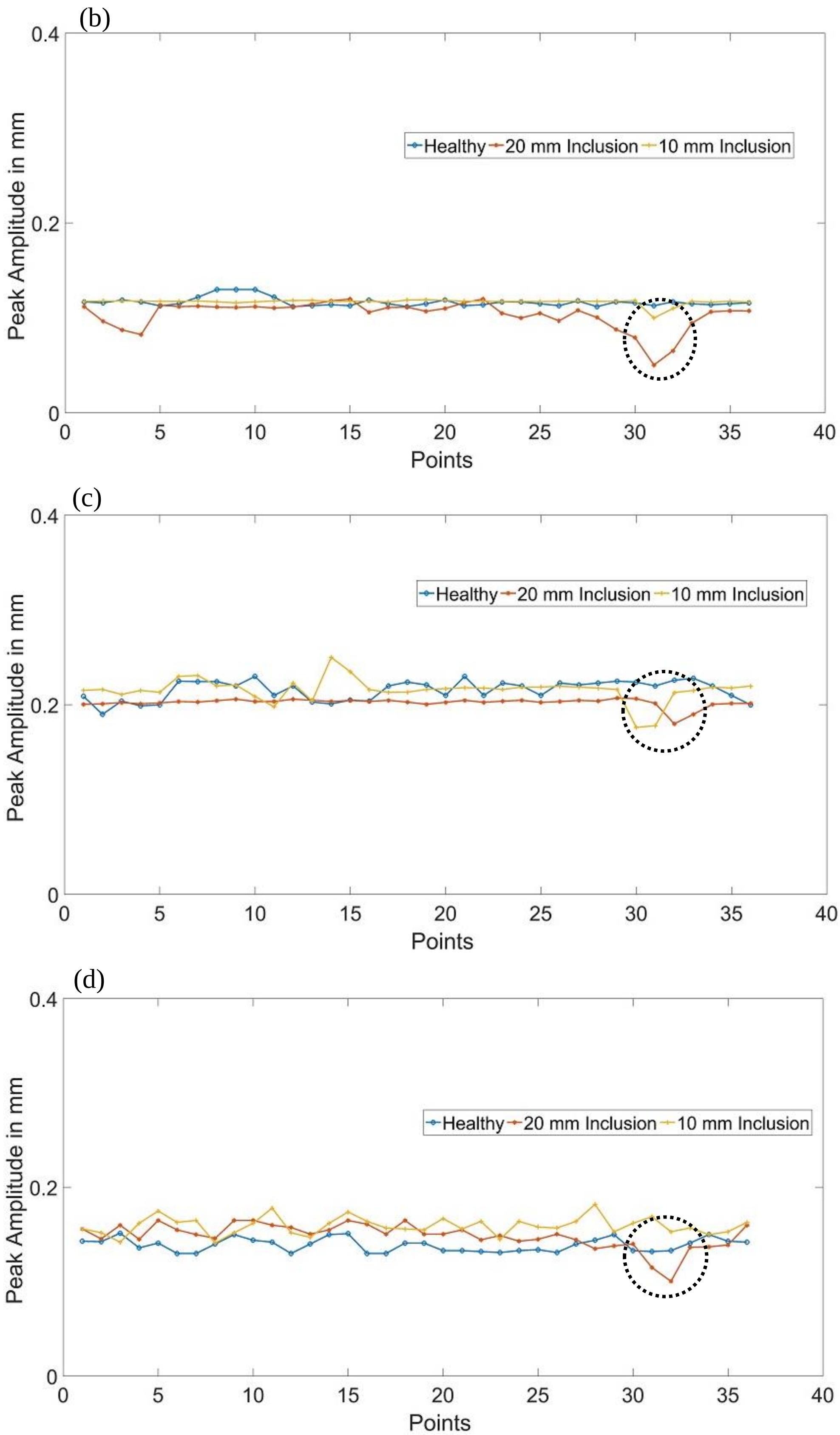
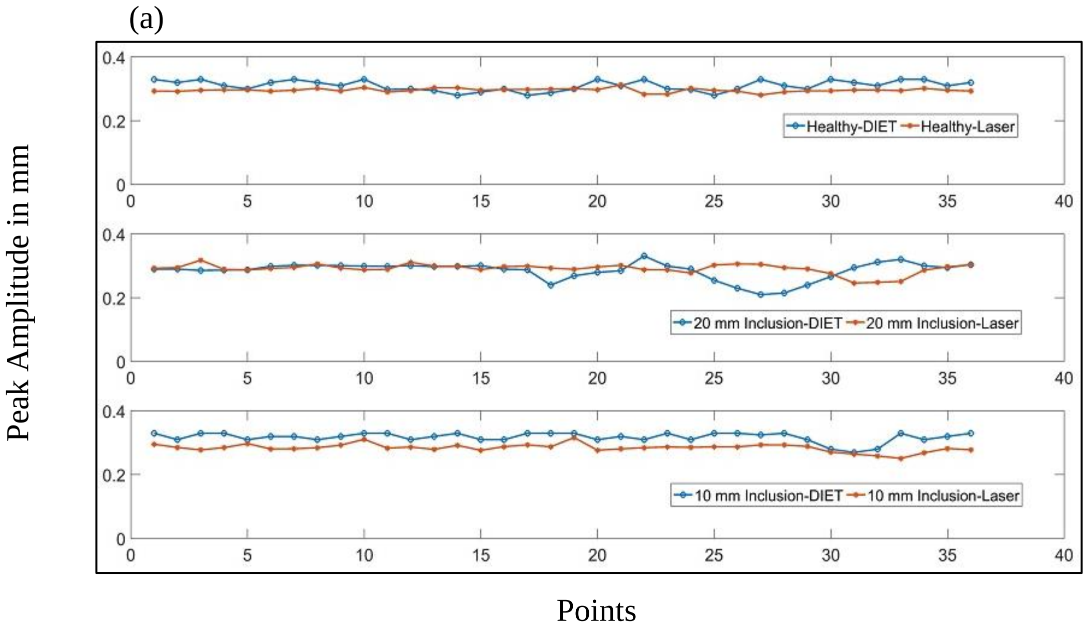


Figure 7. DIET OF experimental data - excitation amplitudes of 1mm peak to peak on phantom surface (a) 16 Hz excitation; (b) 24 Hz excitation; (c) 32 Hz excitation; (d) 40 Hz excitation

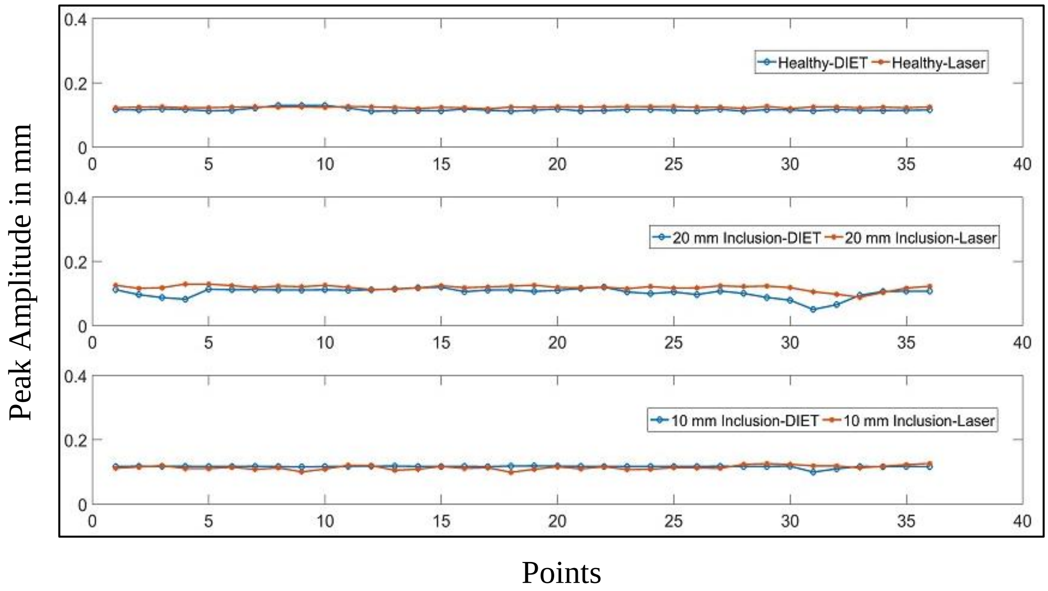
Figure 8 compares separate DIET OF and laser doppler experimental data for each frequency and phantom. Table 1 shows the calculated percentage error range for all 36 surface points between laser doppler and DIET OF for all three phantom cases. Almost all errors are less than 8 %, which is a very good agreement and 90 % of errors are less than 5 %.

It is in on-going pilot clinical trials and per those trials 8mm tumors have detected down and thus it is acceptable. However, a low error <10% on measurements of 10-50 microns (μm) absolute is very good for a low cost system [21].

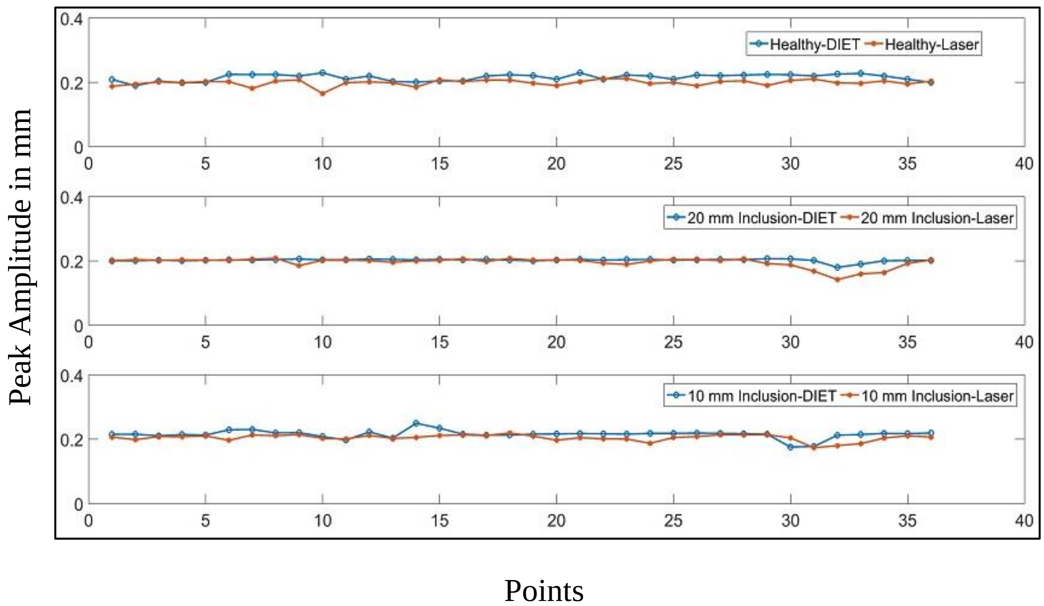
The phantoms in particular are used for this validation, rather than real breasts due to their repeatability. They are thus a good foundation on which to validate methods such as OF involved in DIET [7, 21]



(b)


Healthy-DIET
Healthy-Laser
20 mm Inclusion-DIET
20 mm Inclusion-Laser
10 mm Inclusion-DIET
10 mm Inclusion-Laser
Peak Amplitude in mm
Points

(c)


Healthy-DIET
Healthy-Laser
20 mm Inclusion-DIET
20 mm Inclusion-Laser
10 mm Inclusion-DIET
10 mm Inclusion-Laser
Peak Amplitude in mm
Points

(d)

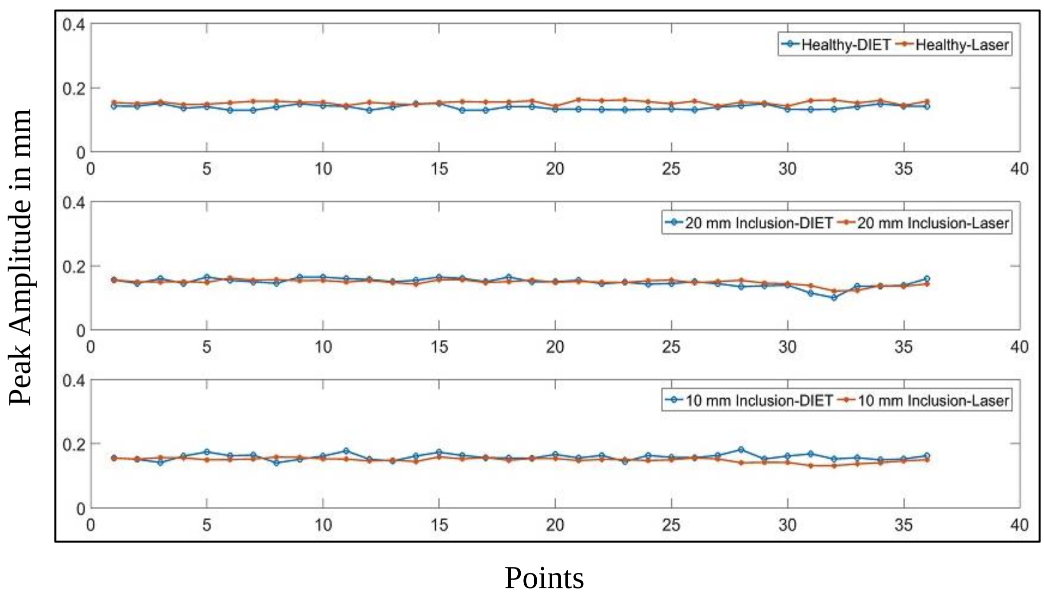

Healthy-DIET
Healthy-Laser
20 mm Inclusion-DIET
20 mm Inclusion-Laser
10 mm Inclusion-DIET
10 mm Inclusion-Laser
Peak Amplitude in mm
Points

Figure 8. Peak amplitude of DIET and laser Doppler vibrometer experimental data (a) 16 Hz excitation; (b) 24 Hz excitation; (c) 32 Hz excitation; (d) 40 Hz excitation

Table 1. Summary of absolute errors between LDV and DIET OF overall input frequencies

Range of error in %			
Frequency	Healthy	20 mm Inclusion	10 mm Inclusion
16 Hz	0.0 - 4.6	0.0 – 7.8	0.0 – 7.8
24 Hz	0.0 – 5.4	0.0 – 6.9	0.0 – 4.9
32 Hz	0.0 – 1.6	0.0 – 4.1	0.0 – 1.9
40 Hz	0.0 – 4.2	0.0 – 4.2	0.0 – 2.7

Overall, these results show DIET OF can accurately capture surface motion of these silicone phantoms, as validated by the laser Doppler vibrometer. However, there are several limitations using a laser Doppler vibrometer that may play a role. One of the main limitations is the difficulty of realizing perfect alignment between the investigated target and laser beam. In addition, there is always environmental noise, but this noise is very small for this laser Doppler vibrometer. In all cases, the error appears very consistent with no apparent bias. Hence, the OF method can be conducted to provide lower error motion with resolution in order of 20 μm, 50 μm, 10 μm, and 20 μm for 16 Hz, 24 Hz, 32 Hz and 40 Hz, respectively.

4. Conclusions

The results of the laser Doppler validation of DIET OF indicate that the method works well. The overall average absolute error for 16 Hz, 24 Hz, 32 Hz, and 40 Hz are 20 μm, 50 μm, 10 μm, and 20 μm respectively, which indicates that the OF method has good resolution. In addition, 90% of errors between LDV and DIET OF data are < 5 %, and this shows that DIET OF tracks points very well. Overall, the OF method is thus validated against a gold standard and its resolution level is quantified. Knowledge of both of these metrics is necessary to develop optimal breast cancer diagnostics from OF measured DIET motion data. In particular, the results from the OF motion algorithm used with DIET and a laser Doppler vibrometer shows the OF algorithm captures surface motion of breast shaped silicone phantoms with good accuracy. Thus, the results justify that OF algorithm is thus suitable and robust enough for use in clinical breast screening. In addition, the overall approach was relatively simple, and could thus potentially be generalised to human breast geometries in future work.

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